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INVESTIGATION OF LUNAR SURFACE CHEMICAL CONTAMINATION BY LEM DESCENT ENGINE AND ASSOCIATED EQUIPMENT

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SUMMARY

This report of an oral presentation on contract NAS 9-4860 "Investigation of Lunar Surface Chemical Contamination by LEM Descent Engine and Associated Equipment," given at NASA/MSC on November 2, 1965, summarizes work already completed on the contract and describes the goals to be reached by the end of the contract. For completeness, several topics are covered in greater detail than at the NASA/MSC presentation. Various comments, suggestions, and questions raised by the audience at that presentation have been incorporated in this report. Topics considered include: composition of inorganic, organic, and bacteriological contaminants, distribution of contamination on the lunar surface, contamination of the lunar atmosphere, transient temperature distributions produced by rocket exhaust plume impingement on the lunar surface, possible chemical reactions between exhaust products and surface materials, and possible interactions between contaminant molecules and the surface. In the Conclusion, the goals to be reached by the end of the contract are listed, and contamination problems that should receive study but are beyond the scope of the present contract are suggested. The conclusion also urges that contamination considerations should receive careful attention in planning the Apollo scientific mission, since the cumulative contamination of succeeding missions may prevent the gathering of accurate data in certain scientific areas. Thus, the door to entire fields of experimental lunar research may close forever after the first manned mission.

ATTENDEES AT NASA/MSC PRESENTATION

November 2, 1965

Attendees	Agency
Julius S. Dohnanyi	Bellcomm
Noel Hinners	Bellcomm
Leonard Aronowitz	Grumman
T. Luzzi	Grumman
R. Oman	Grumman
A. Buchler	A. D. Little, Inc.
Alexis Pastuhov	A. D. Little, Inc.
T. L. Knox	Lockheed Elec.
J. A. Thompson	Lockheed Elec.
Whitney Bartlett	NASA - MSC
James A. Chamberlin	NASA - MSC
U. S. Clanton	NASA
W. R. Cunningham	NASA - MSC
Edward M. Davin	NASA - HQ
John E. Dornbach	NASA - MSC
Dallas Evans	NASA - MSC
D. A. Flory	NASA - MSC
T. H. Foss	NASA - MSC
Forrest G. Hall	NASA - MSC
John W. Harris	NASA
L. D. Hoover	NASA - MSC
W. W. Kemmerer	NASA - MSC
Jerry Kenney	NASA, MSC, ET-34
E. A. King	NASA, MSC, ET-33
Norman Land	NASA - Langley
Curtis Mason	NASA - MSC
David S. McKay	NASA, MSC, ET-33
Keith Richardson	NASA - MSC
Robert C. Runnels	NASA, MSC, ET-34
W. R. Scott	NASA - MSC
Anoris A. Staklis	NASA
John Summerford	NASA - MSC
D. D. Swint	NASA
James E. Townsend	NASA - MSC
Bob Ward	NASA
Ralph Rockow	TRW-STL

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I. INTRODUCTION

The first manned mission to the moon may be the last chance to get relatively uncontaminated lunar scientific samples. Unfortunately, because of previous unmanned missions, the pre-Apollo lunar environment cannot be entirely uncontaminated. However, Apollo may give scientists the opportunity to learn facts about lunar history, the structure of the lunar atmosphere, the possible natural synthesis of prebiological organic compounds in space, and other phenomena that will become increasingly obscured by the cumulative contamination of subsequent manned missions to the moon. Thus, every opportunity should be taken to make the best scientific use of the Apollo mission.

It would be desirable to collect pristine samples from the moon to be returned to earth for analysis. This is probably not possible since, in addition to the above-mentioned pre-LEM contamination, the Apollo mission itself provides copious sources of contaminants. The purpose of this contract is to determine the nature and distribution of LEM contamination on the lunar surface and to determine means for minimizing and compensating for it.

This report of an oral presentation on Contract NAS 9-4860, given at NASA/MSC on November 2, 1965, summarizes work already done on this contract and describes the goals to be reached by the end of the contract. Grumman Aircraft Engineering Corporation is prime contractor and Arthur D. Little, Inc. is a subcontractor. For completeness, several of the topics are treated here in greater detail than at the NASA/MSC presentation. A number of comments, suggestions, and questions raised by the audience at that presentation have been incorporated in this report.

The list of attendees at the presentation (see p. iv) indicates the strong interest in the subject of lunar contamination and suggests the wide variety of fields affected by this study. A few aspects of the Apollo mission thus affected are: sample analysis, instrument design (including the types of hand tools used by the astronauts), sample collection, packaging techniques, and the schedules to be followed by the astronauts in collecting samples.

The degree of "contamination" or "purity" of a lunar sample should not be considered independently of the type of analyses to be performed upon it (this is discussed further in Section V). For certain analyses, the presence of mere traces of one species of contaminant may make the sample unsuitable, while other contaminant species may be present in relatively large amounts without interfering with the measurements. It would be mutually helpful for scientists who are considering possible experiments on the lunar samples to communicate with us. We may be able to advise them where levels of contamination deleterious to their proposed analyses are likely to be encountered in the lunar samples. Conversely, since many species of contaminants may be present, they can advise us about investigating more intensively those specific species that may be troublesome in their analyses. Their informing us about such specific species will enable us to direct our efforts toward finding means for minimizing the concentration of these contaminants in the samples.

The subject of lunar contamination by the Apollo mission is too extensive to be covered completely in the present contract. Additional topics which should receive further study are discussed briefly in the Summary. These topics include: experimental investigation of bacteriological contamination, effects of rocket exhaust gas penetration into the lunar surface, distribution of LEM and space suit leakage, contamination resulting from pre-Apollo missions, development of a time history of contamination of the lunar atmosphere, chemical reactions in the lunar radiation environment and the effects of rocket exhaust gas on instrument packages stationed on the lunar surface.

II. THE LUNAR ENVIRONMENT

A. Atmosphere

The nature of the lunar atmosphere is largely speculative. There are indications that it has an upper limit of 10^{-13} of the terrestrial atmosphere, roughly a million particles/cm^3. The total mass of the lunar atmosphere probably lies in the range of a hundred to a million earth tons (Ref. 1). Estimates of the composition of the atmosphere are generally limited to nonchemically reactive gases since little is known about reactions between the lunar atmosphere and the lunar surface. Such reactions would influence the composition of the atmosphere considerably. Table 1 shows estimates of the composition of the lunar atmosphere made by a number of investigators. This table points up the large differences that exist between various estimates. References to the literature of the lunar atmosphere are found in Refs. 1-4.

B. Surface

We have avoided choosing too limited a set of lunar surface models. While the choice of a small set of specific models allows the calculation of various contamination effects in great detail, it suffers from the obvious disadvantage that such calculations may turn out to be meaningless if Surveyor and other missions show that the lunar surface does not correspond to the chosen models. Therefore, the set of models shown in Table 2 was selected after discussions between Grumman and Arthur D. Little, Inc. The set of models is very general, and can include most of the hypothesized lunar surface structures. Note that particulate matter is intended to include particles of any size, including dust. The set of models is sufficiently flexible so that electrostatic effects, solar wind sintering, dendritic structure, and other proposed details of the lunar surface structure can be fitted into the analysis.

C. Meteoroid Environment

Meteoroid impacts on the lunar surface are a mechanism by which physically or chemically adsorbed contaminants on the surface can be desorbed. The desorbed contaminants may be subsequently readsorbed, may become part of the lunar atmosphere, and/or may be dissipated into space. Since the lunar atmosphere is so rarefied, continuous desorption of gas from the surface may produce appreciable long term atmospheric contamination effects.

TABLE 1

DENSITY OF GASES AT THE BOTTOM OF THE LUNAR ATMOSPHERE FOR VARIOUS VALUES OF SOLAR WIND FLUX

Gas	Density	Solar Wind Flux	Reference
	10^5 particles/cm^3	10^9 particles/cm^2-sec	
H	0.05	1	3
	0.4	10	3
H_2	0.12	1	2
He	0.2	1	3
	2	10	3
H_2O	1.4	1	2
	0.02	1	3
	0.01	10	3
CO_2	1.4-3.4	1	2
A	2.5*	1	4
	0.25*	10	4
	0.4	1	3
	0.2	10	3
A^+	2×10^{-3}	1	3
	2×10^{-3}	10	3
Ne	0.7	1	3
	2.5	10	3
Ne^+	10^{-3}	1	3
	2×10^{-3}	10	3

*Assuming that the only important atmospheric loss mechanism is solar wind scattering.

TABLE 2

LUNAR SURFACE MODELS

1. Homogeneous particulate
2. Homogeneous vesicular
3. Homogeneous solid
4. Two-layer particulate-vesicular
5. Two-layer particulate-rock
6. Two-layer vesicular-rock
7. Rubble
8. Particulate and rubble

Two factors involved in determining the rate of desorption by meteoroids are 1) the meteoroid flux, i.e., the number of meteoroids of mass, m, striking a unit area of lunar surface per unit time, and 2) the amount of contaminant desorbed by each impact including desorption resulting from impacts on the surface of ejecta torn from the surface by the initial meteoroid impact. Estimates of 1) are found in Refs. 5-8. There are large discrepancies between various estimates. There is also a lack of data concerning the flux at small values of m. Upper limits on 2) may be estimated using Refs. 6 and 9. Both 1) and 2) are areas in which considerable experimental work remains to be done. The best available estimates will be used for calculating desorption by meteoroids. The solar wind (Ref. 3) and thermal desorption also provide contaminant desorption mechanisms that may be considerably more significant than meteoroid desorption.

D. Thermal Environment

In Fig. 1, a graph of computed lunar temperatures for one lunation (approx. 29.5 days) is shown that agrees closely with experimentally observed values (Ref. 10). The horizontal line near the bottom corresponds to touchdown at a longitude of 45° with respect to the terminator and a stay of 12 to 44 hours (Ref. 11). Current thinking indicates a touchdown point between 15° and 45°, and a maximum stay of 36 hours. The initial Apollo mission may be shorter than 36 hours. Considerations of launch windows and sleep-work schedules indicate a minimum stay period of 12 hours.

E. Pre-LEM Contamination

Appreciable contamination of the lunar surface will occur before the Apollo mission as a result of Ranger, Surveyor, and Lunik missions. In fact, certain localized portions of the moon are already highly contaminated as a result of hard landings. Subsequent soft landings will undoubtedly produce more widespread contamination. The pre-LEM contamination must be considered as part of the Apollo environment. However, it is not included in the scope of the contract, nor in the present study.

III. SOURCES OF CONTAMINATION

The sources of contamination considered in the present study are the inorganic, organic, and bacterial products in the descent rocket exhaust, and the gas vented from ascent stage cabin and space suit leakage. Sources of contamination that have not been considered include the following:

A. Reaction Control System Rockets

The composition of the exhaust of the Reaction Control System (RCS) rockets is essentially the same as the composition of the descent rocket exhaust. The mass of gas involved in the RCS exhaust is smaller than that for the descent engine. It was considered unnecessary to include the effects of the RCS exhaust since they will be masked by the contamination from the descent engine exhaust.

During discussions at the oral presentation, a member of the audience took the following exception to neglect of RCS rocket contamination. He pointed out that part of the Far Field Contamination study includes calculations of relatively small concentrations of the descent engine exhaust contaminants on areas of the lunar surface distant from the touchdown point. He suggested that at certain of these distant areas, the contribution of contaminants from the RCS rockets might not be negligible compared to that from the descent engine. This suggestion might prove to be true in certain regions far from the touchdown site. However, for regions that the astronaut will be able to sample on the Apollo mission, which are of prime interest to this contract, RCS contamination will be masked by the far larger descent engine contamination.

B. Induced Radioactivity

During its trajectory in cislunar space, the LEM will be exposed to high energy particle radiation. Some atoms of LEM material may undergo nuclear reactions and become sources of induced radioactivity. Some of this radioactive material may be eroded from the craft's surface during the touchdown maneuver and may be deposited in the neighborhood of the vehicle, forming a source of radioactive contamination. Table 3 shows some possible reactions that may take place. In the table, Fr is the fraction of LEM material that can suffer conversion into radioactive substances.

TABLE 3

RADIOACTIVITY INDUCED PER cm^3 OF ELEMENT
BY A PROTON FLUX OF $10^7/cm^2$-sec

Transition	Fr	Half Life	Radiation
$Al^{27}(p,n)Si^{27}$	6.3×10^{-18}	4.2 sec	β^+, γ
$Mg^{24}(p,n)Al^{24}$	5.8×10^{-18}	6.5 sec, 7×10^5 year	β^+, γ
$Fe^{56}(p,n)Co^{56}$	6.1×10^{-18}	77 days	β^+, γ
$Fe^{57}(p,n)Co^{57}$	1.0×10^{-17}	267 days	β^+, γ
$Fe^{58}(p,n)Co^{58}$	1.1×10^{-17}	9 hrs, 71 days	β^+

The amount of radioactive contamination from this source will be so minor that it can be considered negligible. Concern with induced radioactivity would only arise if a type of sample analysis was being considered that showed unusual sensitivity to radioactive contamination.

C. Propellant Quantity Gauging System

The Propellant Quantity Gauging System (PQGS) uses radioactive sources as part of the instrumentation. The strength of the sources and character of the radiation are such that they will produce negligible radioactive contamination.

D. Radiothermal Generator

The Radiothermal Generator (RTG) is a neutron source of considerable strength. It was considered that this might be an appreciable source of radioactive contamination. However, subsequent to the oral presentation, this possibility was discussed with Mr. D. G. Wiseman, Chief Engineer of the Experimental Project Office. He indicated that sensitive particle radiation counters are being considered for use in some instrument packages to be stationed on the lunar surface. Since the RTG must be shielded sufficiently to eliminate interference with these counters, he considers the probability of its producing any appreciable radioactive contamination in lunar surface samples to be negligible.

E. Pre-LEM Contamination

See Section II.E.

IV. CONTAMINANT COMPOSITION

A. Descent Engine

1. Combustion Products

These are the largest source of contaminants. The fuel is unsymmetrical dimethylhydrazine, $(CH_3)_2N_2H_2$. The oxidizer is nitrogen tetraoxide, N_2O_4. The composition of the combustion products is shown in Table 4. This composition was calculated using a Grumman computer program (Ref. 12) and assumes that the chemical composition is frozen near the throat of the nozzle. These results are sufficiently accurate for the principal constituents. However, due to uncertainties in reaction rates and other combustion parameters, some of the minor constituents may be present in amounts appreciably different from those computed. It would be impractical to compute the amounts of these trace compounds more accurately. If a constituent of the exhaust is suspected as being potentially troublesome for a particular type of scientific analysis, it would be logical to measure experimentally its concentration in the exhaust.

TABLE 4

COMBUSTION PRODUCTS IN LEM DESCENT ROCKET EXHAUST

Exhaust Composition	Mole Per Cent
H_2O	36
N_2	32
H_2	13
CO	9.6
CO_2	3.7
H	1.9
CH	1.6
NO	0.24
O_2	0.15
O	0.14

Trace amounts of N, CHO, NH (10^{-4}); NH_2, H_2O_2, NH_3, NO_2, N_2O, HNO (10^{-5}); HCN, HNCO, CH_2O, HNO_2 cis and trans (10^{-6}); e^-, NO^+ (10^{-7}); OH^-, CN (10^{-8}); C (10^{-10}).

It was pointed out during discussions at the oral presentation that while the descent engine is being shut down prior to touchdown, combustion may be incomplete and unreacted fuel or oxidizer may also be present in the exhaust.

In addition to combustion products, some of the helium used to pressurize the propellant system will appear in the exhaust. Helium is an inert gas and is too light to be permanently retained in the lunar atmosphere. Therefore, helium is not expected to be source of contamination.

2. Ablative Material

Composition of the Refrasil used in the ablative material is shown in Table 5. Much of the material ablated near the throat resolidifies along the nozzle and only a fraction of it appears in the exhaust.

TABLE 5

COMPOSITION OF 99.4% PURE REFRASIL

SiO_2	99.4%
Al_2O_3	.11
TiO_2	.33
ZiO_2	.017
B_2O_3	.081
K_2O	.0005
Na_2O	.0014
MgO	.0027
CaO	.0042
Fe_2O_3, CuO, Cr_2O_3, MnO	nil

Little data are available on the products that will appear in the exhaust from the phenolic resin. Best estimates indicate that there will be little ash, and the phenolic will decompose mainly into products that are already present from combustion of the propellants. Thus, the phenolic resin is probably not an important source of contaminants. Experimental investigation would be required to determine the exhaust products arising from this source.

B. Contaminants from Biological and Metabolic Processes

Because processes of this type are variable and depend upon many human factors as well as temperature, pressure, and other environmental conditions, quantitative estimates are only approximations. Estimated production rates for various gases and currently accepted levels for maximum allowable concentrations consistent with the astronauts' environmental requirements are shown in Table 6.

Upon decompression of the space capsule preliminary to the exit of the astronauts, the gases will be expelled.

TABLE 6

BIOLOGICALLY PRODUCED CONTAMINANTS

Gas	Maximum Allowable Concentration (lb/lb mixture)	Production Rate (lb/man-hour)
H	2.57×10^{-3}	1.3×10^{-5}
H_2S	6.18×10^{-5}	2.8×10^{-9}
CH_4	2.65×10^{-2}	3.33×10^{-5}
CO	6.45×10^{-5}	1.9×10^{-6}
O_3	2.21×10^{-7}	This depends upon the kinetics of the reaction Peak: 4.4×10^{-5} Ave: 1.5×10^{-5}
NH_3	3.91×10^{-3}	

In addition to these metabolic gases, approximately 118 grams of H_2O vapor will have accumulated in the cabin during the 4.3 hr trip in the LEM. The H_2O vapor content has been estimated from psychometric curves prepared for the environmental cabin conditions (maximum temperature — 81.6°F, dew point — 67.7°F, and relative humidity — 63 per cent). The volume of the space cabin is 235 ft^3. The vapor can undergo numerous photochemical reactions producing an increased concentration of H_2 and atoms of hydrogen, oxygen, and possibly OH radicals.

All of the gases listed in Table 6 result from metabolic processes except the ozone and ammonia. It is postulated that O_3 may be produced via a photodissociation process due to ultraviolet light that may penetrate into the LEM ascent stage followed by a three-body recombination process. The two-step mechanism can be shown as:

$$O_2 + h\nu \rightarrow O + O$$

$$O + O_2 + M \rightarrow O_3 + M \ .$$

The third body, M, can be any particle capable of absorbing the energy released by the exothermic reaction. The NH_3 represents a by-product of the astronauts' perspiration and it, like the O_2 molecule, may undergo photodissociation and yield radicals. Thus,

$$NH_3 + h\nu \rightarrow NH_2^* + H \ (1640\ \text{Å} = \text{effective wavelength}).$$

Initially, the oxygen gas serves as the agent for the pressurization of the space cabin.

It may also be noted that the astronauts' life support system can add water as a contaminant to the lunar environment. However, as indicated in Table 4, water is so large a fraction of the rocket exhaust that the additional water from the life support system probably will not be significant.

C. Bacteriological Contamination

A panel of Grumman biologists and physiologists assembled on October 14, 1965 to consider bacterial contamination phenomena. This panel concluded that the probability of contamination of lunar samples by live or dead organisms approaches 100 per cent. The panel indicated that the sensitivity of bacteriological analyses is such that a contamination level of one viable bacteria/cm^2 may provide detectable contamination. Also, the sensitivity of methods of analysis now being developed is such that a contamination level approaching one nonviable organism/cm^2 may be detectable. This extreme sensitivity emphasizes the importance of bacteriological contamination, particularly in the field of exobiological experiments.

Tests have been made at various locations in which subjects have been sealed in chambers and the bacterial populations in the chamber have been monitored. Tests have previously been conducted at Grumman to determine the effects of the LEM environment on bacteria. Efforts will be made, within the size and scope of the present contract, to assemble and evaluate such data. However, much additional testing will be required to determine the probable amount and composition of bacterial contaminants in the ascent stage, and the amounts that will be distributed by an astronaut during his activities on the lunar surface.

V. CONTAMINANT DISTRIBUTION

A. The Degree of Contamination

The degree of contamination of a given sample should be judged in terms of the analyses that will be performed on it. In Section IV.C, it was indicated that a sample that might be considered hopelessly contaminated by a biologist planning an exobiological experiment could be rated as being free from contamination by a geologist. Both Grumman and Arthur D. Little, Inc. are investigating the amount of contamination that is considered significant in various types of analyses. Distribution of contaminants from the descent engine plume on the lunar surface will be so widespread that, in a sense, no portion of the lunar surface will escape. However, the total mass of the Apollo contaminants is insufficient to form a coating one monolayer thick if uniformly distributed over the surface of the moon. The rough estimate in Fig. 2 assumes that there are on the order of 10^{15} sites/cm^2 on a surface, each of which must be covered by a contaminant molecule in order to form a monolayer. Thus, even if the surface of the moon were perfectly smooth, it would require an amount on the order of 10^4 tons of water to form a monolayer on the entire surface. The total mass of the propellant combustion products is only a tiny fraction of this amount. Thus, the concentration of contamination can be expected to decrease to very small levels with increasing distance from the touchdown point. Maps of the distribution of contaminants on the surface will be, therefore, an important tool in compensating for contamination. For certain types of analyses, such maps may indicate that the astronaut need collect samples at distances of only a thousand feet or less from the LEM so that they can be considered relatively uncontaminated. Such distances are within the astronauts' range. The maps may also indicate that, to secure samples with tolerable contamination levels for more sensitive types of analyses, the astronaut would have to travel prohibitively large distances from the LEM. In this case, means must be developed to reduce or compensate for the contamination in the collected samples. The thousand-foot maximum range is taken from the AMPTF Design Reference Mission (Ref. 13), portions of which have become obsolete. A revised version will soon be available. Recent calculations of maximum range based on faster walking rates may increase the above value by a factor of two or three. However, on the initial manned mission the astronauts may limit their excursions to less than the maximum attainable range.

To facilitate analysis of the distribution of exhaust plume contaminants, the study of distribution has been divided into two main categories. The first, which we term "Far Field Contamination," occurs when the LEM is sufficiently distant from the lunar surface so that gas dynamic interactions between the plume and the surface may be neglected. In the second, "Near Field Contamination," complicated interactions between the plume and the surface must be considered.

B. Far Field Distribution

The gas plume issuing from the LEM descent engine deposits contaminants on the lunar surface. The plume has two major flow regimes. Adjacent to the nozzle exit there is a compressible continuum fluid flow regime. As the gas expands outward from the nozzle, the density decreases and a far field free molecular flow regime develops. The Far Field Distribution considers the intersection of the plume with the lunar surface when the LEM is sufficiently distant from the moon so that only the far field flow regime of the plume intersects the surface.

A computer program is being prepared that will determine the flux of contaminant molecules at each point on the lunar surface. If all the molecules are assumed to stick to the surface (sticking probability = 1) the initial impacts of molecules with the surface will determine the contaminant distribution (see Section VIII). Should the sticking probability be less than unity, some of the molecules will rebound from the surface and may "bounce" several times before sticking, or may become a permanent part of the lunar atmosphere or be lost into space. The determination of contaminant distribution when the sticking probability is less than unity will require further analysis.

The model used for calculating the flux of far field molecules to the surface is shown in Table 7. The moon is treated as a smooth sphere. The exhaust is treated as a point source of molecules, all of which move with the same speed. The assumption of a point source is justified by the relatively large distance of the LEM from the surface. The uniform speed assumption is justified since in the continuum regime the average macroscopic velocity of molecules is relatively independent of molecular weight, and at the boundary of the regime the Mach number is sufficiently high so that the random thermal velocities of the molecules are small compared to the macroscopic velocity. The assumption of an axisymmetric molecular flux density distribution from the point source is a good representation of the actual plume density distribution.

TABLE 7

FAR FIELD CONTAMINATION MODEL

LEM Descent Rocket Engine

Free molecular point source

a. Uniform velocity

b. Density distribution is axisymmetric about the nozzle centerline and varies inversely with the square of the distance from the source center

Flow Field Between LEM and Lunar Surface

Free molecular trajectory flow due to the lunar gravitation force field

Exhaust Gas Impact on Lunar Surface

Full accommodation (no rebounding)/partial accommodation

Contamination Composition

Homogeneous contamination (no separation of species due to thermal velocity variation)

The versatility of the computer program is indicated by the list of input parameters in Table 8. Any LEM trajectory can be included in the program. Any orientation of the LEM at each point along the trajectory can be included. The exhaust speed (speed of the molecules) is an input parameter. The axisymmetric point source molecular flux distribution can be taken from a theoretically or empirically derived analytic function or from a table of experimentally determined values. A method of characteristics is presently being used to determine the density distribution. For preliminary design of the computer program the trajectories in Ref. 13 have been used. More recent trajectory information will be used in the preparation of maps (Refs. 11, 14, and 15).

TABLE 8

FAR FIELD CONTAMINATION CALCULATION

TIME DEPENDENT INPUT DATA

LEM Landing Trajectory

a. LEM trajectory coordinates (r, Θ_L, Δ)

b. LEM velocity (q_{LEM})

c. LEM velocity direction relative to LEM position (Θ, Σ)

Descent Rocket Engine

a. Exhaust velocity (q_J)

b. Rocket nozzle centerline orientation relative to LEM velocity (α, β)

c. Exhaust density function distribution $[D(\varphi)]$
(φ - exhaust direction relative to nozzle centerline)

The calculations performed by the program are indicated in Table 9. A fixed impact point is selected on the lunar surface. The coordinates of this impact point are given with respect to the touchdown point to facilitate preparation of maps of contamination distribution in the neighborhood of the landing site. At each position of the LEM along its trajectory, the flux of contaminant molecules at the impact point is determined using the factor F which gives the expansion of the plume between the engine and the surface. The flux is then integrated along the LEM trajectory to get the total contaminant molecule flux at the impact point.

TABLE 9

FAR FIELD CONTAMINATION CALCULATION

Select a Fixed Impact Point on Lunar Surface $(\bar{\theta}_m, \bar{\delta})$

Determine Time History of the Contamination Flux $[I = I(t)]$

a. Impact Point Local Coordinates (θ_m, δ)

b. Trajectory Initial Point Velocity Components $(q_r, \bar{q}_p)$

c. Flow Expansion Factor Between Rocket Exhaust and Impact Point (F)

d. Rocket Exhaust Direction Relative to the Nozzle Centerline (φ)

e. Trajectory Results at the Impact Point

1. Contamination Flux (I)

2. Impact Angle (φ_m)

3. Impact Velocity (q_m)

Integrate Contamination Flux Time History to Get the Total Contamination at the Fixed Impact Point $[C(\bar{\theta}_m, \bar{\delta})]$

The angle and velocity at which the molecules impact are also calculated. These parameters are important in determining sticking probabilities (see Section VIII).

C. Near Field Distribution

The Near Field Distribution considers the contamination of the lunar surface that occurs when the continuum region of the descent engine rocket plume contacts the lunar surface. Shock waves in the plume, erosion of surface material, and heating of the surface are factors in determining the composition and distribution of contamination of the surface and in the atmosphere.

Material eroded from the lunar surface by the rocket plume is expected to be heavily contaminated by direct contact with the exhaust gas. Eroded material that is redeposited on the lunar surface may form an important source of sample contamination. Therefore, the distribution of redeposited material is being investigated using a theoretical lunar surface model consisting of a smooth layer of spherical particles of uniform but arbitrary radius. A computer program is being developed to calculate the rate of erosion of the surface, the distribution of redeposited material, its temperature history, and the amount of contamination adsorbed on the particle surface. Since the adsorbed contaminants may undergo chemical reactions on the particle surface, the composition of the contamination may be affected by the temperature history of the particle during erosion. For these reasons, the thermal history of the particle resulting from heating by convection and radiation from the exhaust will be calculated.

In addition to contamination by eroded material, the surface and atmosphere will suffer contamination caused by contact with the exhaust gas. This contamination will occur, of course, even if the lunar surface does not erode. The distribution of gas adsorbed on the surface and atmospheric contamination will be determined (see Section VI).

The complexity of the near field problem is indicated by Fig. 3 where the exhaust from a vertically oriented rocket is shown impinging on a model of the lunar surface. An inviscid hypersonic continuum flow regime extends from the nozzle exit. Near the axis, the flow passes through a shockwave into an inviscid subsonic continuum regime where it is turned away from the axis. The boundary layer in the flowing gas at the surface may make a transition from laminar flow to turbulence. The flow of gas at the surface generates stress that can erode particles. The particles will be transported by the flowing gas. The density of the gas decreases as it flows away from the axis and the flow enters a transition regime and then a noncontinuum free molecular flow regime. In the noncontinuum regime, the particles are no longer carried along by the gas but will follow ballistic trajectories in the gravitational field until they strike the lunar surface. The location of the impact of a particle on the surface is determined by the particle's position and velocity as it enters the noncontinuum regime.

The characteristics of the gas flow field and the rate of erosion will be calculated utilizing the erosion studies of Roberts (Refs. 16, 17, and 18). The eroded particles are transported by the gas. The various ways in which particles can be transported by the gas (Ref. 19) are shown in Fig. 4. Small particles are entrained (suspended) in the gas and carried along by it. A computer program previously developed at Grumman by R. Grossman (Ref. 20) to determine velocity of particles eroded by a rocket exhaust is being adapted to calculate the motion of suspended particles. Massive particles, too heavy to be picked up by the gas, may "creep" along the surface. Particles of intermediate size, too large to be completely suspended in the gas, can be picked up into the gas stream; they will then fall to the surface and bounce back again into the gas stream. Because such particles move in a series of hops, the process is termed saltation. Creep and saltation are commonly encountered in the blowing of sand in terrestrial deserts (Ref. 19). An analysis of particle transport by saltation is being made at Grumman.

The temperature of the eroded particles is being calculated by investigating the convection and radiation of heat from the rocket gas to the particle. Radiation to the particle is calculated by a method commonly used in thermal engineering. Details of this method are found in Ref. 21. The emissivity of the plume gas is evaluated at the appropriate pressure and temperature in a spherical cavity of radius equal to the so-called "beam length" (Ref. 22). The radiation from the plume is then assumed to be equal to the radiation from a sphere of gas of uniform thermodynamic properties. The diameter of the sphere is taken to be the distance between the legs (primary struts) of the LEM. A proper pressure, temperature, and beam length are selected for each species of gas in the exhaust. The radiation to the particle from each species is calculated and radiation from all the species in the exhaust is then summed to determine the total radiation to the particle.

The convective heat transfer to a particle in the continuum flow is obtained from a dimensional analysis. The expression for heat transfer is

$$Nu = .37\, Re^{0.6}\, Pr^{0.33} \,, \qquad (1)$$

where Nu is the Nusselt number, Re is the Reynolds number, and Pr is the Prandtl number of the flow. The expression for heat conduction into a spherical particle under a heating rate boundary condition is

$$\bar{v} = 2\,\frac{(V - v_o)}{r} \sum_{n=1}^{\infty} e^{-\kappa k_n^2 t}\, \frac{a^2k_n^2 + (ah - 1)^2}{k_n^2\left[a^2k_n^2 \quad ah(ah - 1)\right]} \sin k_n a \sin k_n r \; , \tag{2}$$

where k_n are the roots of

$$ah - 1 + ak_n \cot k_n a = 0 \tag{3}$$

and $\bar{v}$ is the temperature difference between the gas and the sphere, V is the initial temperature of the sphere, v_o is the temperature of the gas, h is the ratio of convective film coefficient to the thermal conductivity, r is radial distance from the center of the sphere, κ is thermal diffusivity, t is time, and a is the sphere radius. Equation (2) is a modified form of the solution of the heat transfer equation appearing in Ref. 23. The solution was rederived in the present study to include the combined boundary condition of nonzero surface temperature and nonzero gas temperature. A Grumman computer program for calculating the transport properties of rocket exhaust gas is being adapted for use in the convection calculation. Heat convection will be averaged over the surface of the sphere to eliminate the necessity of considering aerodynamic distributions in the gas around the sphere that would severely complicate the calculation. Possible chemical kinetic effects at the surface of the sphere will not be considered.

The surface of a particle and the surface of the moon will be contaminated by contact with gas in the continuum flow regime. The number, N, of contaminant molecules adhering to the area, A, of a surface (per unit time) is given by

$$N = G\alpha A \; , \tag{4}$$

where G is the flux of contaminant molecules to the surface, and α is the "sticking probability" (the probability of a molecule of a given species sticking to the surface when it impacts). The value of α may change as the surface becomes progressively more contaminated. Sticking probabilities are discussed in Section VIII. Similar considerations apply to contamination by the gas in the noncontinuum flow regime, the principal difference between contamination between the two regimes being in the calculation of G.

The initial calculation of Near Field Contamination will be made with a "steady state" program. In this program, the exhaust rocket will be assumed to be at a fixed altitude and the rates of eroded material build-up and contamination on the surface will be calculated. The total contamination can then be determined by dividing the actual descent trajectory into a number of intervals and summing the steady state values for each interval.

In Fig. 5, a computer program for solving the entire steady state problem is shown diagrammatically. The rocket engine parameters and particle sizes are given as inputs. Using Roberts' model, the gas flow field characteristics are found. From Roberts' model, the rates of erosion are calculated and from a model for the transport of particles, the particle trajectories are calculated. The distribution of eroded particles impacting on the surface is calculated. The adsorption of gas on the particle surface is calculated. The convective heat transfer to the particle is calculated. The radiative heat transfer to the particle is calculated. The convective and radiative transfer are summed and the particle temperature is determined. The "reduced trajectory" in the upper right corner of Fig. 5 is a refinement introduced into the calculation of radiative heat transfer to particles that are being moved by the saltation process. Since particles moving by this process hop along, a particle near the surface will be shaded from the radiation by particles above it. The reduced trajectory is a scheme for determining a properly weighted average trajectory that excludes the complications introduced into the computation by hopping but will give the correct value of radiative heat transfer. It must be noted that the time and manpower limitations of the present contract will not allow programming in detail all of the sections shown in Fig. 5. To provide adequate and useful maps by the end of the contract period, suitable simplifications will be made (see Section X.A.3).

D. Space Suit Leakage and Vented Gas

As indicated in Section III, space suit and ascent stage atmospheres are a source of contaminants, particularly bacterial contaminants. The importance of space suit leakage is apparent since the astronaut will closely approach, and may possibly even come in contact with, the samples he is collecting. Therefore every sample collected by an astronaut will have had space suit leakage squirted at it.

The distribution and the rate of leakage from a space suit, which is of the order of several hundred cc per minute, will be influenced by the astronauts' activities. Tests should be made of the rate and location of suit leakage while the astronaut is engaged in activities simulating sample collection procedures on the Apollo mission.

When leakage rates and locations are determined, the distribution of contamination which they will produce can be calculated in a relatively simple manner. However, in view of the limited time period and size of the present contract, it has been decided not to pursue this question. Instead, our efforts have been directed toward the investigation of the probable composition and amount of bacteriological contamination, and toward the establishment of appropriate methods of reducing or compensating for space suit and ascent stage leakage contamination.

E. Thermal Distributions

The structure and composition of lunar surface materials may suffer phase changes and other physical or chemical reactions as a result of lunar surface heating by the impinging exhaust plume. Possible chemical reactions that may take place between contaminants and lunar surface materials or chemical reactions between various species of contaminants on the lunar surface will be strongly influenced by the surface temperature. Temperature distributions produced on the lunar surface by the descent rocket plume were previously calculated at Grumman. The thermal conductivity of the lunar surface was assumed to be zero. Since measurements of lunar radiation indicate that the lunar surface has low thermal conductivity the calculated values are probably well within the required accuracy. Some calculated thermal distributions for various LEM altitudes are plotted in Fig. 6.

It is desirable to have additional information about the distribution of temperature with depth below the lunar surface, and about the cooling rates after the rocket has been turned off. Therefore, the data on heat flux to the lunar surface which was used at Grumman to perform the thermal distribution calculations, has been forwarded to Arthur D. Little, Inc. Under a subcontract, they will use a temperature distribution computer program developed for NASA by the Harvard College Observatory. They will determine the transient temperature distribution in several selected models of the lunar surface, including stratified models. Suitable ranges for the thermal parameters will be chosen for these models.

VI. ATMOSPHERIC CONTAMINATION

Contamination of the lunar atmosphere by the descent engine exhaust will be investigated analytically. Several scientists have proposed experiments which involve long term measurements of the composition of the atmosphere. Such measurements will require a knowledge of the time required after touchdown for contamination to decrease to a level low enough for data which is representative of an uncontaminated atmosphere to be taken. This study will determine the history of contamination due to various contaminant species in the exhaust. The rate of decrease of contamination level as a result of atmospheric loss mechanisms will be calculated.

The significance of this topic may be judged by the fact that the total mass of LEM propellant may be of the order of 10 per cent of the estimated mass of the lunar atmosphere (see Sec. II.A). Although not all of this propellant will enter the lunar atmosphere, contamination may be appreciable.

In addition to contamination which enters the atmosphere directly from the exhaust, the long term history of lunar contamination will be influenced by contaminant species which are adsorbed on the lunar surface and subsequently desorbed (Ref. 24). The expected rates of desorption which can be anticipated in the lunar thermal, meteoroid, and solar wind environment are being surveyed (Sec. II.C).

VII. CHEMICAL REACTIONS

The composition of the principal combustion products in the descent engine exhaust, which is the largest source of contaminants, is given in Table I. Water will be the most abundant reactive contaminant. Significant amounts of hydrogen atoms and hydroxyl radicals will also arrive unreacted at the lunar surface. Because of the total quantity of combustion products, such minor constituents as the CHO and the NH radicals will still constitute significant amounts in absolute terms.

In addition to contaminants originally present in the exhaust, other compounds may be formed by chemical reactions between contaminants, or between contaminants and lunar surface materials. Arthur D. Little, Inc. is studying under subcontract the thermodynamic possibility of certain chemical reactions. In addition, they are examining how the lunar radiation environment will influence these chemical reactions.

The influence of the radiation environment may be pronounced. Reactions which are thermodynamically possible do not always take place. For example, at room temperature, the possible reaction of a mixture of oxygen and hydrogen to form water or the conversion of diamonds into graphite proceed at rates which are effectively zero. However, under the effects of the radiation environment, the lunar surface may become covered with catalytic sites which could greatly accelerate the rates of certain reactions. Also, radiation may play a direct role in causing certain reactions. Compare, for instance, the role of radiation in the production of ozone and ammonia discussed in Section IV.B. Photochemical reactions will require further investigation.

The reactions of constituents with one another under the influence of radiation or catalytic sites might produce such problems as the reaction of CO or CO_2 with H_2, possibly yielding carbohydrates as a final product.

Possible reactions of exhaust products with a lunar surface model which assumes the surface to consist of a mixture of silicates are being examined. In this case, the most likely area of reaction will be near the point of descent of the LEM, where temperatures of about 1000°C (1300°K) may be reached. The possibility of hydrolysis of the silicates at this temperature has been examined. Free energies for some possible reactions are shown in Table 10. Except for the possible oxidation of ferrous silicate, the results show that hydrolysis of the silicates is not likely.

TABLE 10

REACTION OF WATER VAPOR AND SILICATES

FREE ENERGY OF REACTION AT 1300°K

Reaction	ΔF, kcal
$Na_2SiO_3(c) + H_2O(g) \rightarrow 2NaOH(g) + SiO_2(c)$	+29.8
$Na_2SiO_3(c) + H_2O(g) \rightarrow 2NaOH(\ ) + SiO_2(c)$	+23.6
$MgSiO_3\ (c) + H_2O(g) \rightarrow Mg(OH)_2(c) + SiO_2(c)$	+23.0
$Fe_2SiO_4(c) + H_2O(g) \rightarrow Fe_2O_3(c) + SiO_2(c) + H_2(g)$	+ 5.6

The hover period may produce significant lunar surface effects. During this period, according to Ref. 13, the LEM may cover a distance of as much as 400 feet while hovering at an altitude of perhaps 200 feet above the lunar surface. Estimates of the exhaust gas pressure at the surface indicate that an area of the order of 20,000 square meters may be contaminated during hover. During this time, it is probable that there will be no significant effects from either direct heating of the ground by the exhaust or from erosion effects, so that only the interaction between the exhaust gas and the relatively cool lunar surface need be considered. During this period of the order of 100 kg of water, 5 kg of hydroxyl radicals, and gram amounts of free radicals such as CHO and NH may be deposited on the surface. The above estimate that the LEM will travel a horizontal distance of 400 feet at an altitude of 200 feet, taken from Ref. 13, has been superseded by more recent trajectory calculations. However, comparable conditions will occur during the Lo-Gate to Pre-Touchdown phase of these more recent trajectories (Ref. 14). It is possible there will be significant effects on the surface appearance of the hover area due to contamination by the exhaust products. If, for instance, the dark color of the moon is due to unsaturated or electronically excited sites, one may conceive of the approach of the LEM as possibly saturating these sites and turning the area into a lighter color. Similarly, if there is the equivalent of an electrical double layer on the surface of the moon, e.g., charged surface and an oppositely charged layer of dust above it, the effect of the contamination during the hover period may be to discharge this double layer.

VIII. MOLECULAR INTERACTIONS WITH THE LUNAR SURFACE*

Interactions of molecules with the lunar surface, particularly the sticking of contaminant molecules to the surface, will be treated by using methods developed in the Research Department of Grumman under a contract with the Fluid Physics Branch, Research Division, Office of Advanced Research and Technology, NASA HQ. In this study, a machine program was developed which allows the calculation of the three dimensional classical trajectories of gas molecules directed at a crystal lattice that is represented by a set of harmonic oscillators which are point centers of potential (a Lennard-Jones 6-12 potential). A detailed discussion of this study can be found in Ref. 25. The study allows examination of chemisorption in which the binding energies are of the order of 1-10 ev and also physical adsorption with energies in the neighborhood of .1 ev. Important parameters in the adsorption of gases on the lunar surface are the incident energy of the gas molecules. For Far Field Contamination, the incident molecular energy has been calculated to be of the order of 1.5 ev.

There is considerable basis for presuming that the lunar surface will appear rough to an incoming flow of molecules. An incident molecule may, therefore, be expected to "bounce" several times in the immediate vicinity of the impact point before escaping from the surface. Thus, unless the sticking probability for a molecule in a single encounter is rather small, the molecule may be expected to be adsorbed by the surface. Molecules with accommodation coefficients of .7 may therefore be considered to have unity sticking probability, while molecules with rather low accommodation coefficients, say of the order of .2, may have a good chance of escaping from the surface without being adsorbed during a single macroscopic encounter. It should be noted that the energy accommodation coefficient is intimately related to the sticking probability.

The most important factor in determining sticking probability will be the binding energy with the surface, the mass ratio between gas molecule and surface atoms, and the natural frequency of the lattice atoms (i.e., their Debye temperature). Since the incident energy will be prescribed by the rocket gas velocity (about .05 ev/atomic mass unit), the binding energy will be important in trapping molecules whenever binding energy is greater than about .5 ev. This will require a clean, mildly reactive surface. Gas molecule masses greater than about 1/3 of the target atom mass will be sufficient to produce high accommodation (and resultant high sticking probability) unless Debye temperatures are quite high. The accommodation coefficients, and hence the sticking probabilities, are highly dependent on the cleanliness of the surface. The computations show that if a monolayer of gas is deposited on a surface, the accommodation coefficients will be characteristic of the new surface layer rather than characteristic of the bulk. Consequently, if the lunar surface is relatively free from gas before Apollo contamination, then the sticking probability of that surface may be expected to increase rapidly once contaminant gases have been adsorbed. A second consequence is that earth-bound laboratory experimental data on accommodation coefficients or sticking probabilities using surfaces that have not been thoroughly outgassed may be irrelevant for molecular-surface interactions on the moon. A molecular beam apparatus for obtaining the parameters needed to determine molecular-surface interactions under conditions in which surfaces are thoroughly out-gassed is being constructed at Grumman

The results of the computer program for the interaction study led to the development of a few relatively simple algebraic expressions for the accommodation coefficients and sticking probabilities (Ref. 25). The accuracy of these analytic approximations should be considerably better than the accuracy with which the parameters involved in interactions between molecules and the lunar surface are known. They will be used to estimate sticking probabilities of contaminant molecules on the lunar surface.

*Grateful acknowledgment is due Dr. R. Oman of the Grumman Research Department for his assistance in the preparation of this section.

IX. MINIMIZING AND COMPENSATING FOR CONTAMINATION

The considerations of Section V indicate that it probably will be impossible to obtain pristine lunar samples from the limited area which the Apollo astronauts can explore. Efforts should therefore be directed toward identifying, minimizing, and compensating for contamination in samples. Probably the most important tools for this purpose will be maps of the distribution and time history of the various contaminant species. The location and time at which every lunar sample is collected should be recorded. This will allow a statistical comparison between the relative amounts of various species of constituents in the samples and the predicted contaminant distributions. Such a comparison will help distinguish naturally occurring lunar substances from contaminants.

As discussed in Section VII, a study is being made of the possibility of the synthesis of small quantities of various substances by chemical reactions between contaminants in the lunar environment. This study will aid in the identification of such synthesized substances as contaminants.

Several means have been suggested for minimizing bacterial contamination (see Sec. IV.C). The suggestions include ejecting a collector from the LEM prior to venting the ascent stage. The collector would be designed to take a sample of the lunar surface and seal it in a manner that would protect it from subsequent exposure to vented gas or space suit leakage. The collector would be retrieved by the astronaut.

Another suggestion was for an instrument to be used by the astronaut. The instrument would contain a heat source which would sterilize a small area of the lunar surface and a sterilized drill that would take a sample from the sterilized area at sufficient depth so that at least part of the sample would be unaffected by the surface heating. Because of the low thermal conductivity of lunar surface material this depth should not be excessive. The sample would be sealed in such a way that it could be extracted from the surface without suffering contamination from space suit leakage.

X. CONCLUSION

A. Goals

By the end of the contract, the following aspects of lunar surface contamination will have been examined:

1. Lunar Models

A set of lunar models which is flexible enough to incorporate many proposed details of lunar surface structure has been selected. The models are discussed in Section II.B.

2. Contaminant Composition

Composition of the combustion products in the descent engine exhaust has been previously calculated at Grumman. This is discussed in Section IV.A. Composition of the Refrasil ablative material is discussed in the same section. We have been unable to obtain information on the products in the exhaust arising from the phenolic ablative material, but it is indicated that this will not be an important source of contaminants.

The metabolic production of contaminants by the astronauts has been investigated. Composition and rates of production of these products are discussed in Section IV.B.

During the course of the present investigation, the importance of bacterial contamination has become increasingly clear. Its importance arises from the difficulty of avoiding bacterial contamination, and the sensitivity of biological experiments to such contamination (see Sec. IV.C). Bacteriological contamination is also intimately linked to the problem of back-contamination.

A panel of Grumman biologists and physiologists met to consider problems of bacteriological contamination. Means for studying the problem and for minimizing such contamination were considered. These means will be further explored (see Sec. IX). Data in the area of bacteriological contamination are insufficient and our investigation has made it evident that an adequate treatment of the problem is beyond the scope of the present contract. Efforts to obtain further information will continue to the end of the contract.

3. Contaminant Distribution

A computer program is being completed which will give the flux of "Far Field" contamination from the rocket plume to every point on the lunar surface (see Sec. V.B). The distribution of contamination on the surface resulting from this flux will be investigated. In the case of unity sticking probability (Sec. VIII) for contaminant molecules on the lunar surface, the contaminant distribution will be determined by the flux. Distributions for the case of sticking probabilities less than unity will be investigated and it is expected that maps of the approximate contaminant distributions for nonunity sticking probability can be prepared by the end of the contract period.

The more complicated problem of "Near Field" contaminant distribution is being studied (Sec. V.C). The erosion of material from the lunar surface by the impinging rocket plume is being investigated using a particulate surface model. A computer program for calculating the thermal history of eroded material as a result of the convection and radiation of heat from the exhaust is being completed. A computer program to determine the distribution on the lunar surface of eroded spherical particles will be prepared. A simplified suspension model and, if time permits, a simplified "saltation" model will be used in this program. These models are considered sufficiently accurate to give order of magnitude results. The computer programs will be constructed in such a manner that more sophisticated models can be incorporated if more accurate calculations are subsequently desired. The computer programs will be used to construct maps of surface contamination which should be accurate to about an order of magnitude.

An analysis will be made of the adsorption of "Near Field" rocket exhaust gas on both eroded material and on the lunar surface. The analysis is expected to be sufficiently advanced by the end of the contract to allow preparation of maps of the distribution of the adsorbed contaminants on the surface.

Temperature distribution produced in lunar surface models by rocket plume impingement will be computed and mapped (Section V.E).

4. Atmospheric Contamination

The time history of the contamination of the lunar atmosphere (see Sec. VI) by the descent engine exhaust plume will be investigated. Rates of desorption for contaminant species which are adsorbed on the lunar surface will be estimated. Desorption must be accounted for in experiments involving long term monitoring of the lunar atmosphere.

5. Chemical Reactions

Possible reactions between exhaust products and the lunar surface have been considered. It has been concluded that, in general, these will probably not constitute a major contamination problem. Exceptions might occur in areas of the lunar surface containing substances of unusual chemical activity. A class of reactions between contaminant species is being studied which could be of importance in specific types of analyses. These are reactions which are catalyzed by sites on the lunar surface which have been activated by the lunar radiation environment. It is suggested that such reactions might possibly produce trace quantities of substances such as, for example, carbohydrates. Such substances could be important contaminants in analyses that are particularly sensitive to them.

It would be advisable for any scientist who is planning analyses of lunar samples to communicate with us. We are now in a position to discuss specific problems of chemical contamination in relation to specific experiments. Such communication would also allow us to direct our efforts to investigation of contaminants to which his experiment is particularly sensitive.

6. Minimizing and Compensating for Contamination

Maps showing the time histories of the distributions of contaminant species are probably the single most useful tool in compensating for contamination (Sec. IX). The study which is being conducted of chemical reactions catalyzed by active sites on the lunar surface is also required to pinpoint the possibility of the synthesis of detrimental contaminants by reactions between species (Sec. VII).

Several suggested methods for minimizing bacteriological contamination are under investigation (Sec. IX).

B. Areas Recommended for Further Investigation

At the end of the current contract, a number of areas requiring further investigation will remain. A few of these areas are listed below. Some of them represent continuations or extensions of present activities; others have not yet been treated.

1. Contaminant Composition

a) Bacteriological Contamination

Much work remains to be done in gathering data on bacteriological contamination. Experimental measurements should be performed on the type and quantity of bacteria given off by personnel wearing space suits in simulated LEM and lunar environments.

2. Contaminant Distribution

a) Maps of Surface Distribution of Contaminants

Maps of distributions of particulate lunar surface materials eroded by the LEM rocket plume impingement will be prepared during the present contract (see Sec. X.A.3). This work could be extended to include the effects of cohesion between particles due to the high vacuum environment, sintering of the surface by the solar wind, and other suggested lunar surface phenomena.

The maps of contamination resulting from adsorption of gas on the lunar surface in both the Near Field and Far Field regimes which will be prepared during the present contract can be considerably improved by a more detailed treatment of the effects of interactions between contaminant molecules and the lunar surface. Continued work in this area is advisable.

b) Penetration of Exhaust Gas into the Lunar Surface

Because of time and manpower limitations, effects of penetration of exhaust gas into the lunar surface will not receive adequate treatment during the present contract. Penetration may produce important contaminating effects in samples obtained by core drills, and may be responsible for producing thermal changes at depths below the lunar surface. The present study should be extended to cover this area.

c) LEM and Space Suit Leakage

Research on distribution of the gas leaking from LEM and space suits has been neglected so that additional effort could be expended on surveying bacteriological contamination (see Sec. V.D). If it is not possible to estimate these distributions before the end of the present contract, it would be advisable to extend the effort in order to allow at least a first order calculation to be made.

3. Pre-LEM Contamination

Pre-Apollo missions will have a relatively small contaminating effect, but it is not evident that these effects can always be neglected (see Sec. II.E). Results of the present study should be extended to the study of pre-LEM contamination.

4. The Lunar Atmosphere

a) Time History

Analytical results will be obtained on this contract on the history of lunar atmospheric contamination. These results can be improved by including more detailed treatments of sticking, accommodation, and desorption of gas from the lunar surface. If there is sufficient interest in the long term history of the lunar atmosphere after the Apollo mission, it would be advisable to continue the present study by including more detailed treatment of the effects of surface temperature variations, molecular velocity distribution, time history of solar wind variations, and other items not included in the present study.

b) Desorption Mechanisms

The long term history of the composition of the lunar atmosphere will be affected by the desorption of contaminants from the lunar surface (see Sec. VI). Various data which are not presently available, such as information on meteoroid fluxes, will probably become available as a result of further satellite, rocket, or earthlaboratory experiments. A limited effort to continue the current study in order to include such data when they become available would be appropriate.

Various experiments should also be performed in order to obtain data not currently available, i.e., the amount of gas desorbed by the impact on the lunar surface of ejecta from meteoroid impacts (see Sec. II.C).

5. Instrument Packages

A number of programs, (ALSEP, etc.) are concerned with instrument packages left on the lunar surface during the Apollo and subsequent missions. Such packages may be affected by heating resulting from contact with the ascent stage exhaust, by impacts from lunar surface material eroded by the ascent engine plume, and descent stage propellant leakage or explosion subsequent to launching of the ascent stage. It would be advisable to extend techniques developed during the current contract to the examination of such problems.

6. Chemical Reactions

a) Catalytic Sites

Possible reactions catalyzed by active sites on the lunar surface (see Sec. VII) should receive additional theoretical and experimental study.

C. The Apollo Scientific Program and Consequences of Cumulative Contamination

The strongest impression left by the oral presentation and subsequent conversations with people concerned with lunar experiments is that the problems of lunar contamination should be given greater weight in planning the Apollo mission scientific program. Many people concerned with programs which involve tool design, experiments, and sample collection techniques are aware of contamination problems and are seeking ways to deal with them. However, people concerned with the over-all planning of the Apollo scientific mission should also be continually aware of the effects of cumulative contamination due to subsequent missions. This is vitally important because certain significant lunar experiments which may be performed on the Apollo mission may be impossible on later missions due to cumulative contamination. It is possible that the door to whole fields of scientific investigation may be forever closed after the first manned mission. Exobiological experiments immediately come to mind because this field has received considerable comment. Undoubtedly, investigation would disclose other areas in which the first Apollo mission may be the last chance to gather data. By contrast, it would be hard to suggest a geological experiment that would be seriously affected by the cumulative contamination of a great number of missions.

It is unlikely that the Apollo mission will be man's last visit to the moon. What is urgently needed is a survey to determine the important classes of experiments which must be performed at the earliest possible date in the course of man's exploration of the moon. Experts in various fields should be consulted in order to stimulate thinking in this area. It is already late, and efforts should begin as soon as possible.

The Apollo scientific program must always be subordinate to the overriding concern for mission safety. But within this limitation, the progressive closing out of important areas of research by cumulative contamination should be a prime factor in planning the scientific program.

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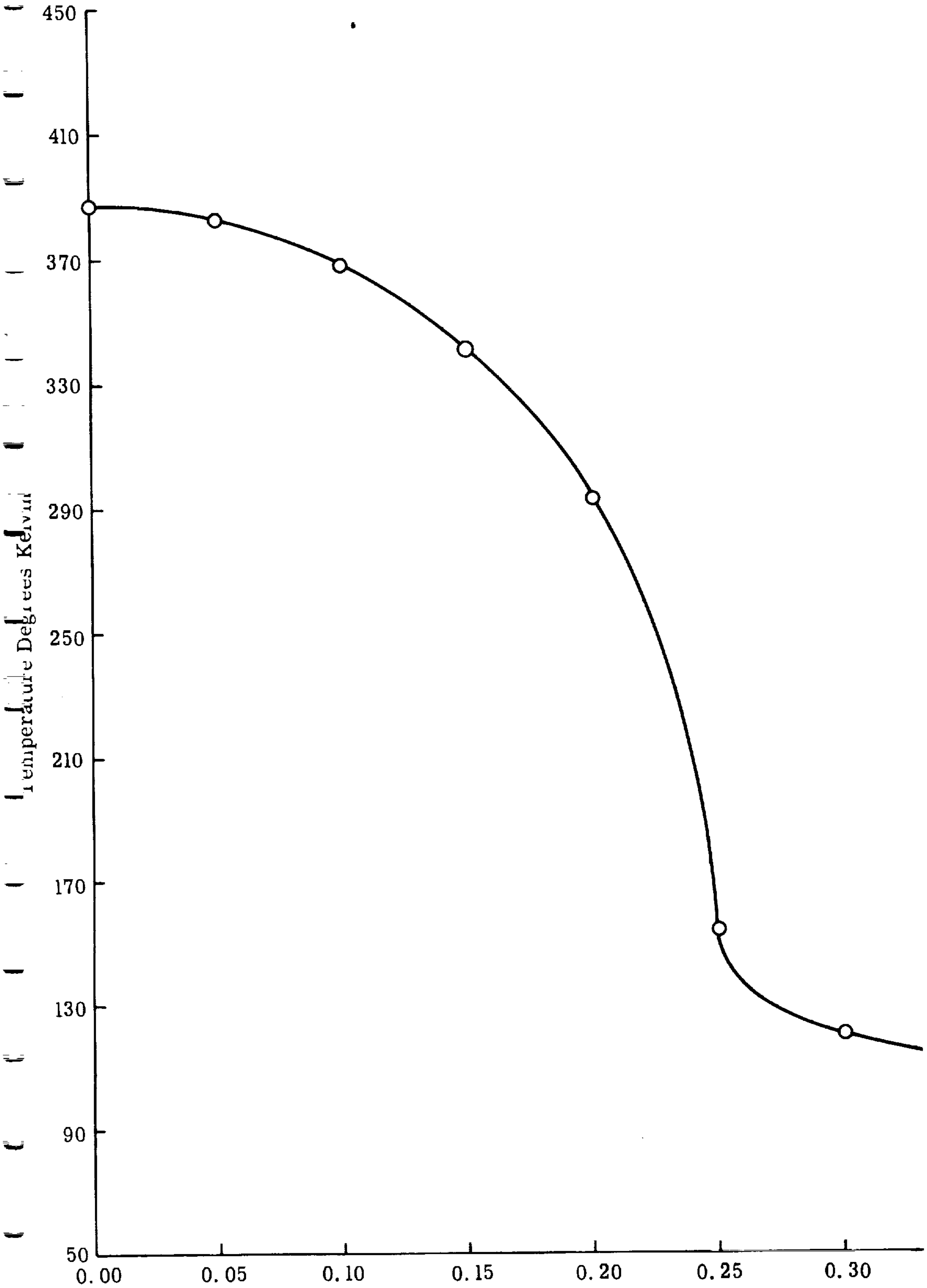


Temperature Degrees Kelvin
450
410
370
330
290
250
210
170
130
90
50
0.00
0.05
0.10
0.15
0.20
0.25
0.30

410

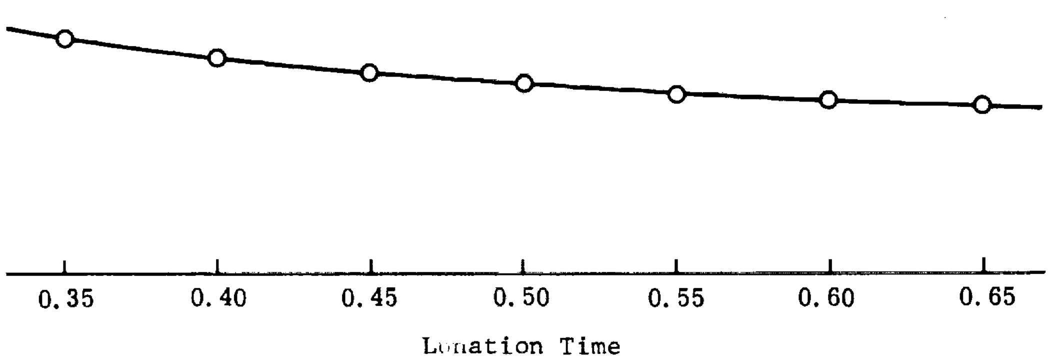
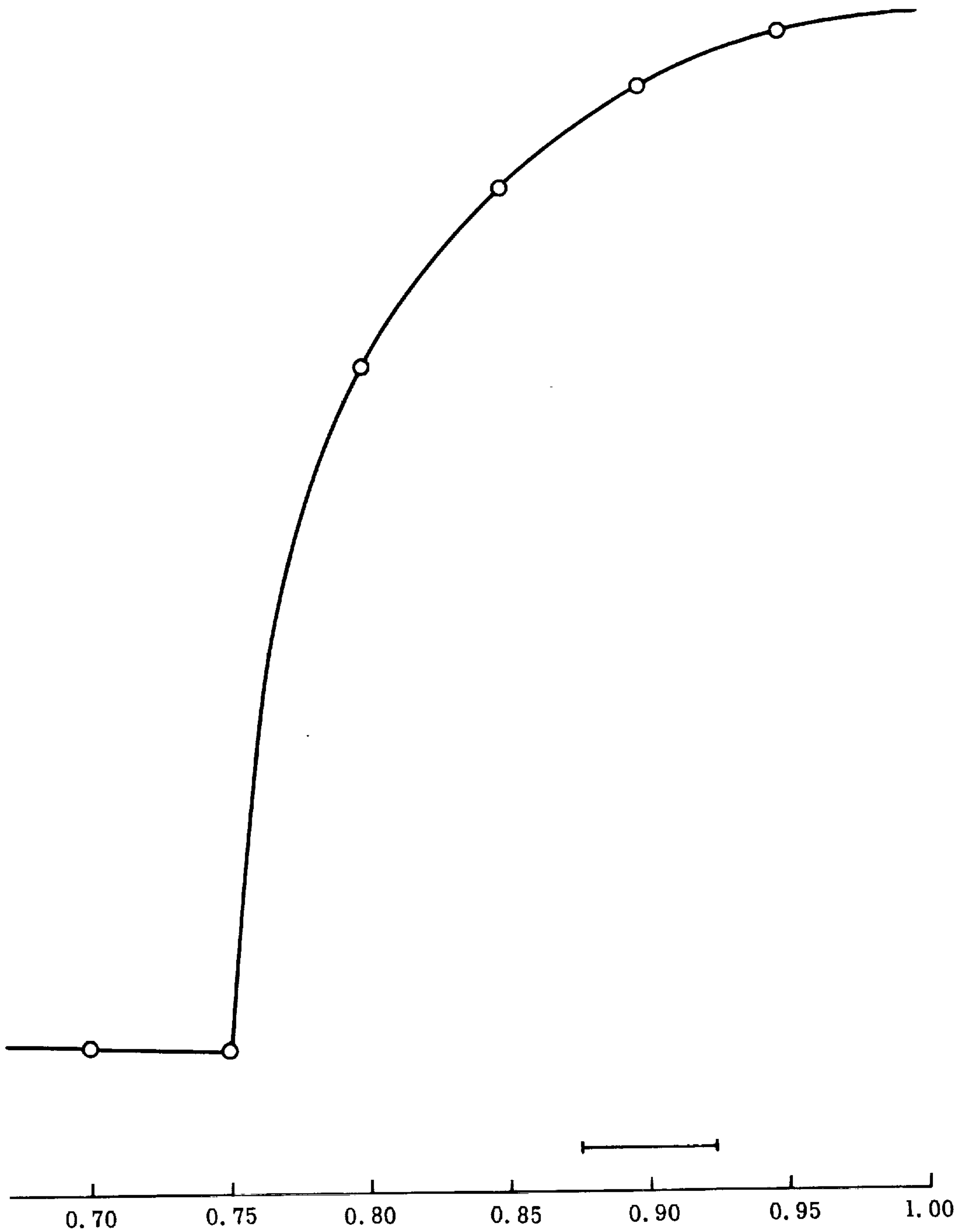


Fig. 1 Lunar Surface Temperature

412



(B)

Lunar diameter	$\sim$ 3500 Km.
Lunar surface	$\sim 3 \times 10^{17}$ cm^2
Monolayer coverage	$\sim 10^{15}$ sites/cm^2
Hence	$\sim 3 \times 10^{32}$ sites on a smooth lunar surface
1 mole	$\sim 6 \times 10^{23}$ molecules

One molecular layer on the lunar surface corresponds to:

$$\frac{3 \times 10^{32}}{6 \times 10^{23}} = 5 \times 10^{8} \text{ moles}$$

One monomolecular layer of water $\sim$ 9000 tons

Arthur D. Little, Inc.

Fig. 2 Contamination of the Entire Lunar Surface

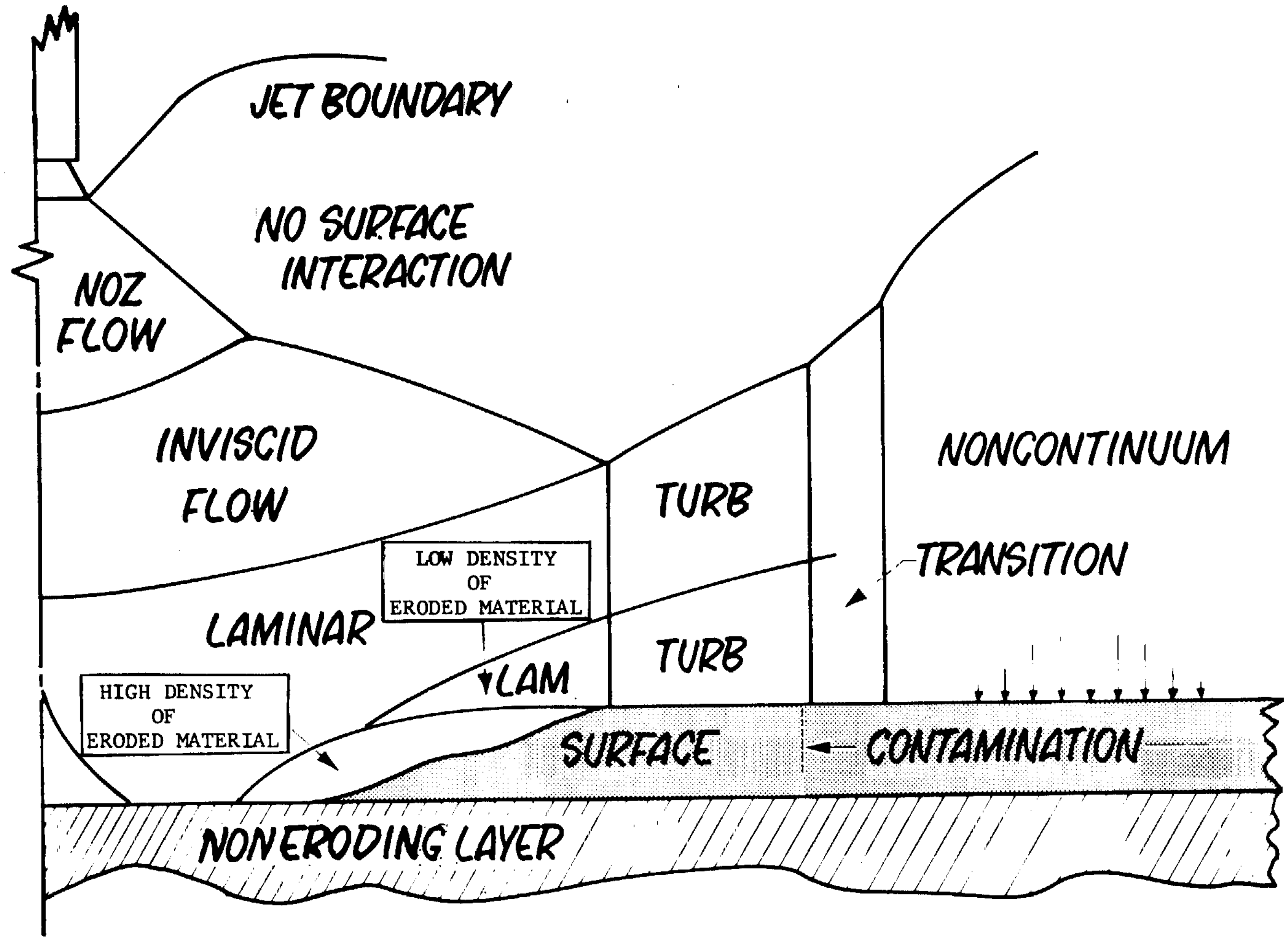


Fig. 3 Flow Regions for Near-Field Contamination

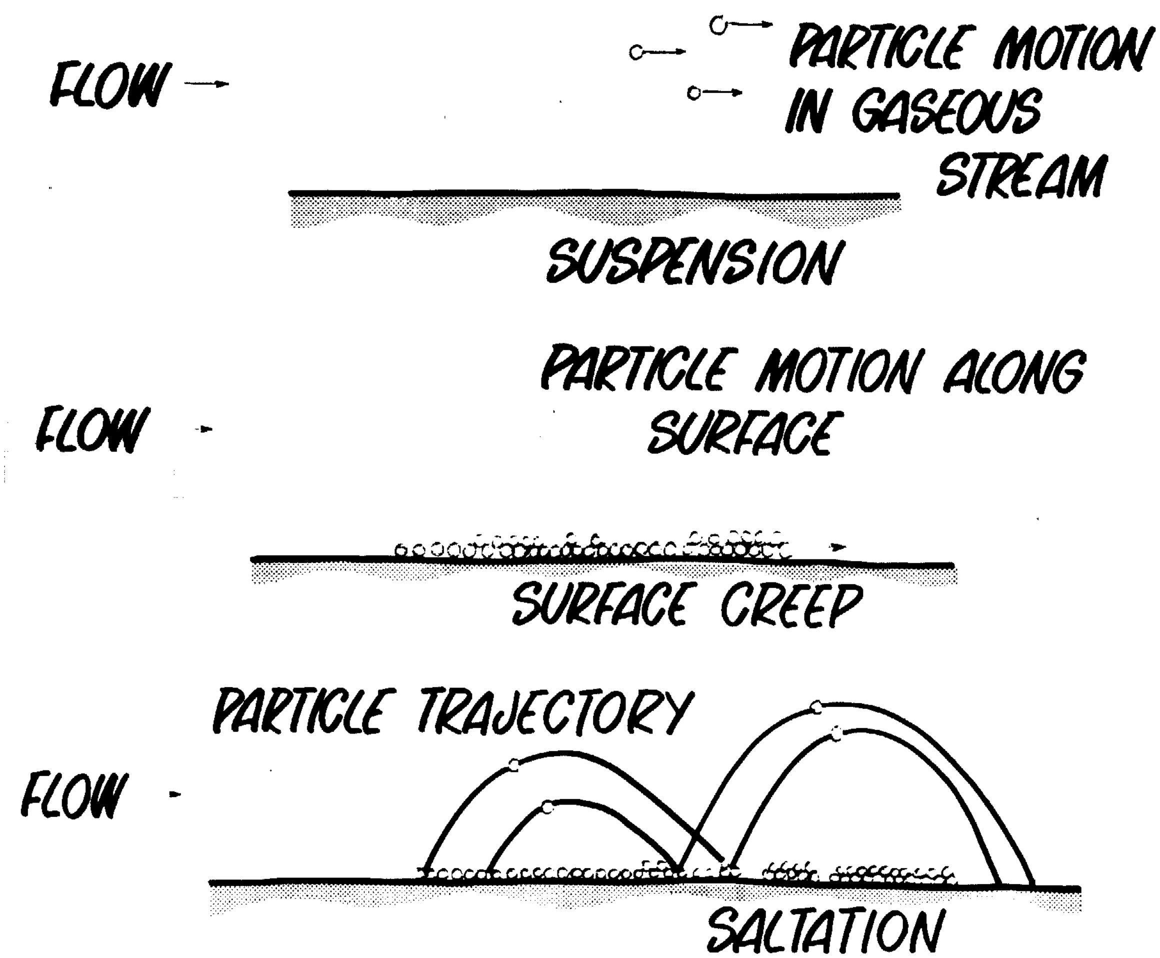


Fig. 4 Erosion: Grain Motion Types

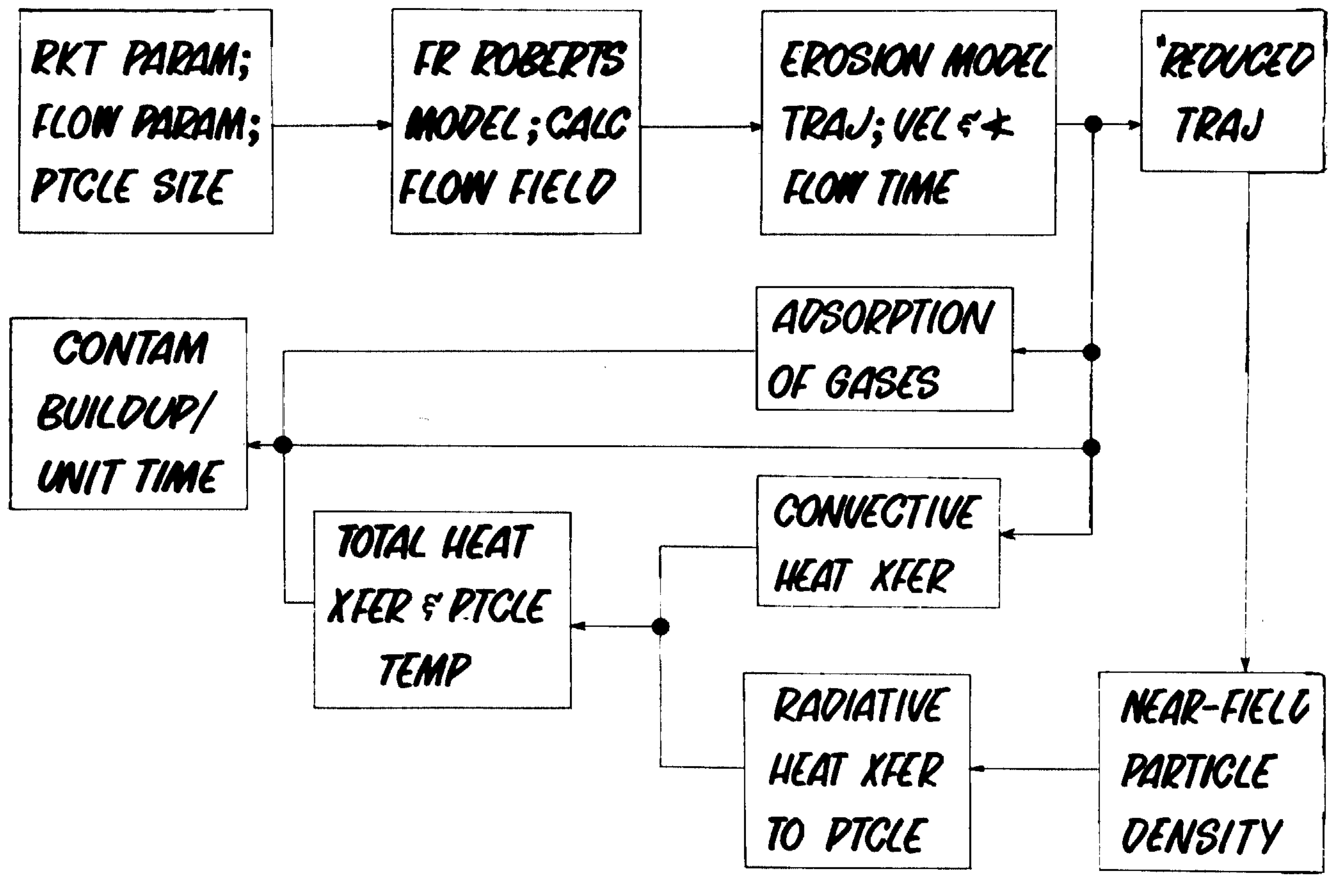


Fig. 5 Steady-State Problem

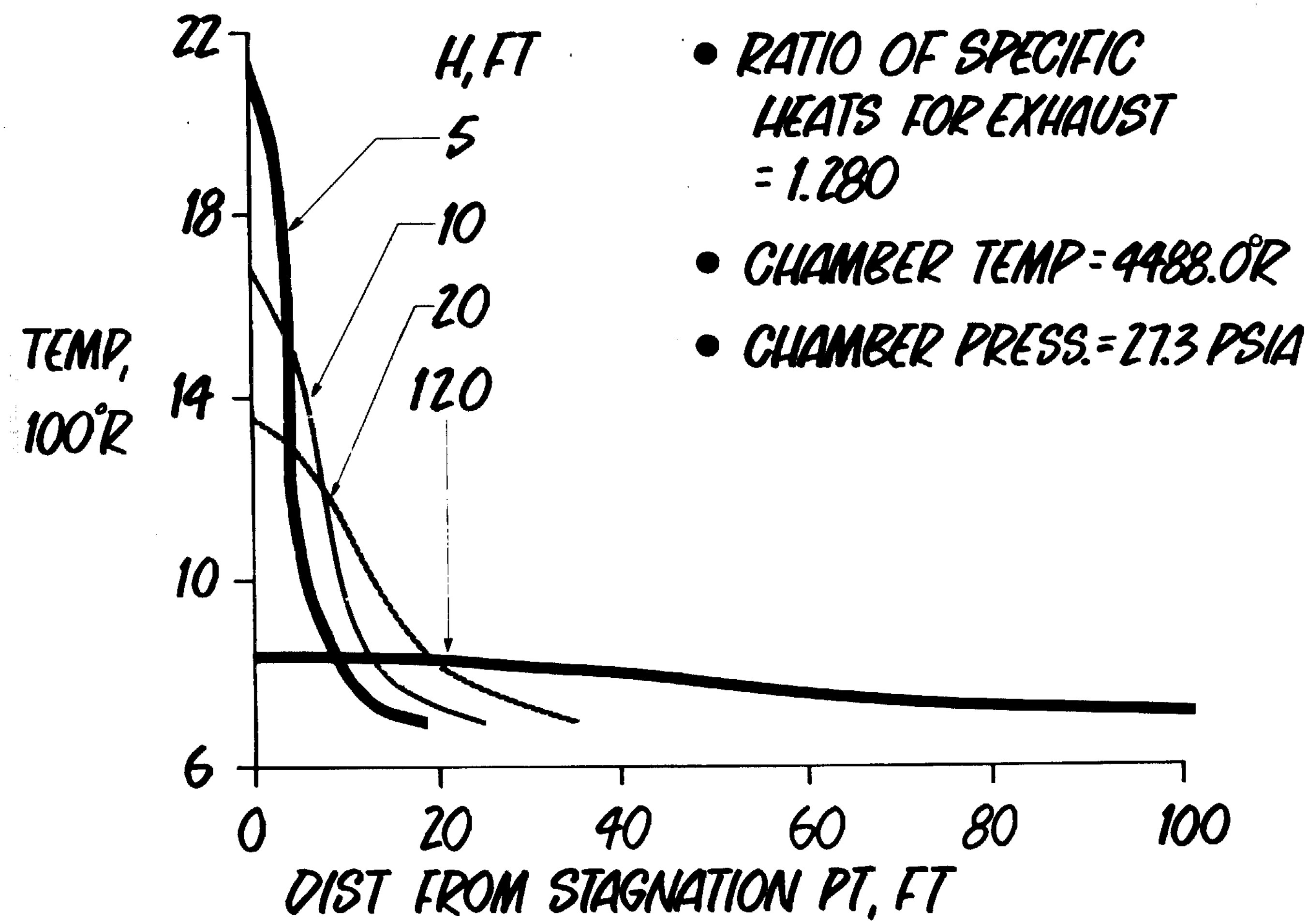


Fig. 6 Lunar Surface Temperature vs. Distance and Altitude